North Dakota Renewable Energy Council

Final Report

Portable Solar Array Modules

Phase I

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Introduction

This document is the Phase I final report for the Portable Solar Array Modules project. Packet Digital, in collaboration with Nishati and NRL, has successfully designed, developed, prototyped, and tested a transportable solar power generation system for remote military installations, emergency shelters, camps, municipalities, security teams, first responders, media broadcasters, and disaster relief organizations (e.g. Red Cross, FEMA). The system consists of two modules that we call as Portable Solar Generator 1 (PSG1) and Portable Solar Generator Companion 1000 (PSG-C1000).

PSG1 is specifically designed to be used with the Nishati's Expedition 570 solar panel. It will extract the maximum available output power from the solar panel and use it for charging BB2590 batteries, providing power through the USB chargers, and providing power through the sharing port output.

PSG-C1000 is specifically designed to be used with the PSG1 and is intended to convert up to 1000W of DC input from the PSG1 (needs two PSG1 in parallel to provide 1000W) into 110V AC with ground fault circuit interrupter (GFCI) protection. The input voltage is compatible with common 6T battery voltages of 28.8V.

Review of the Objective and Primary Results:

This Phase I research and development project has created and demonstrated a portable solar power generation system for providing DC and AC power to the end users. This has been achieved by harnessing solar energy with high-efficiency, durable photovoltaics technology along with advanced Maximum Power Point Tracking (MPPT) and power management algorithms. Under this project, we have created a hybrid solar power harvesting and power distribution system, combining the portability and durability of BB2590 military smart batteries as the energy storage mediums, and solar energy through efficient power conversion circuitry to provide continuous power to the user.

Figure 1: Full system deployment

PSG1 optimizes the power conversion from the solar array to the batteries, from the solar array to the electronics, and from the electronics to the external load. The power conversion circuitry provides state-of-the-art, high-efficiency operations while the microprocessor runs advanced algorithms for MPPT as well as balancing the power distributions.

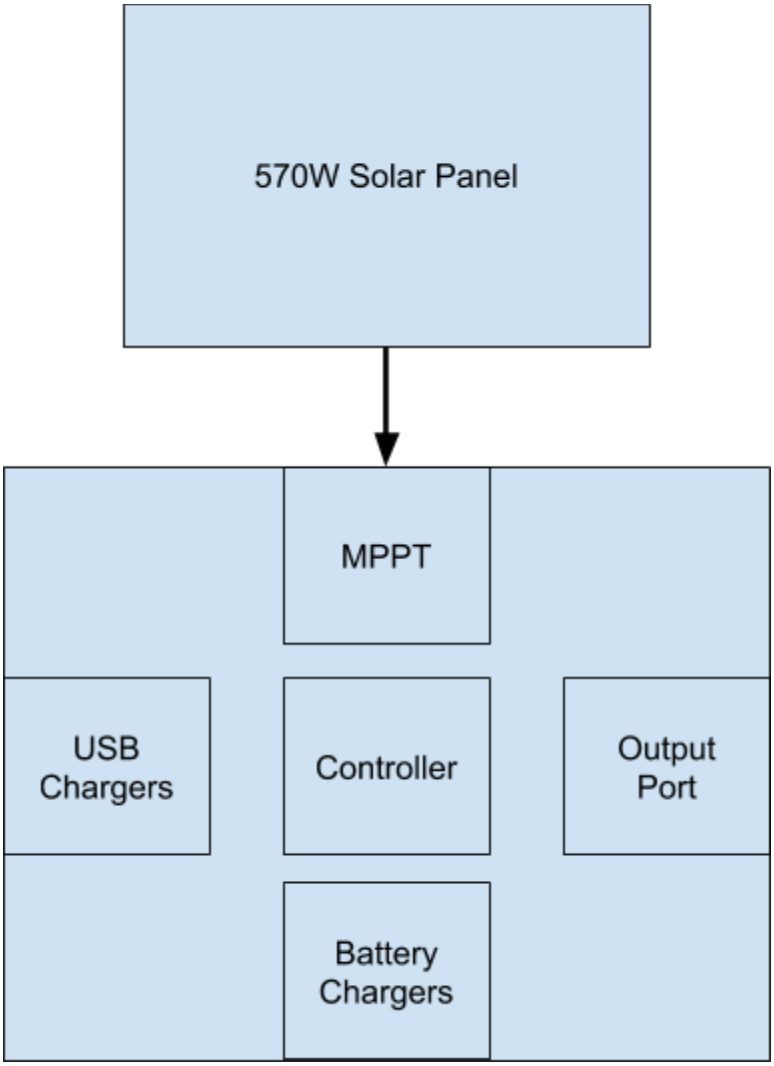

Figure 2: System overview

Schedule

This Phase I project was originally scheduled for a 9-month duration, however due to parts unavailability, it had to be extended for another month. This final report covers the progress made during Phase I.

Deliverables

- Power electronics and hardware for a portable 1kW solar power system, including 1kW inverter, smart batteries, and MPPT

- Innovative MPPT algorithm for extracting maximum charging capacity from the solar cells
- Custom enclosures for individual electronic components and integrated system
- Documented results of system testing
- Manufacturing ready for a commercially viable, portable 1kW solar power system
- Commercialization partners and distribution

Final Status

Objective 1: Specify, select, and test a 1kW inverter.

A high reliability AC inverter is an integral part of the system. It converts the DC power from solar panel and battery to a usable AC voltage. The inverter was selected using the following criteria:

- 1kW rated output
- Tolerate a range of DC input voltage to accommodate different battery state of charges
- Built in cooling
- High (>80%) conversion efficiency
- Pure sine wave output
- Relatively small or compact in form

The Meanwell TS-1000 series meet most of the above criteria as compared to other inverters that we evaluated. It comes from a well respected company in the power industry and it has surge protection up to 2000W. The pure sine wave output will ensure that all electronic devices powered by it will have reliable power without the concern for damaging sensitive electronics. The unit has several smart safety features built in such as a low battery alarm, low battery shutdown, over voltage, over temperature, overload, output short and reverse polarity. For this portable solar generator project, TS-1000-124 was selected.

Table 1: TS-1000-124 general specification

Input voltage	21-30 VDC
Output voltage	110 VAC
Output power	1000W, surge protected up to 2000W
Efficiency	89%
Frequency	50/60Hz (selectable)

Figure 3: Meanwell TS-1000 series

Upon a successful completion of inverter test, Packet Digital assembled the inverter inside a rugged, dustproof, watertight protective case. GFCI protection and cooling fan were added during the assembly. For the cover plate, a custom cut aluminum panel was designed with the help from Red E in Fargo. The fully assembled prototype is called PSG-C1000.

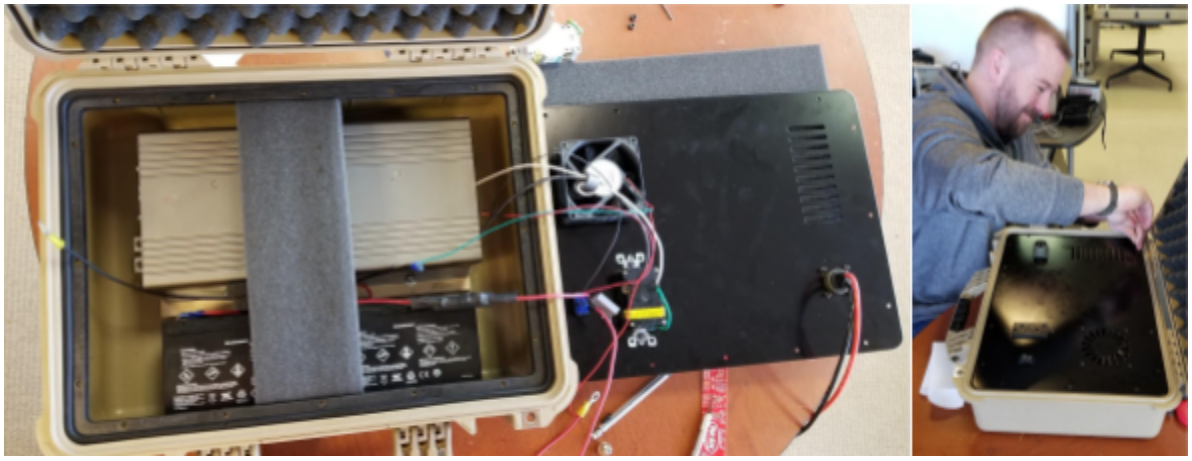

Figure 4: Inverter assembly inside protective case

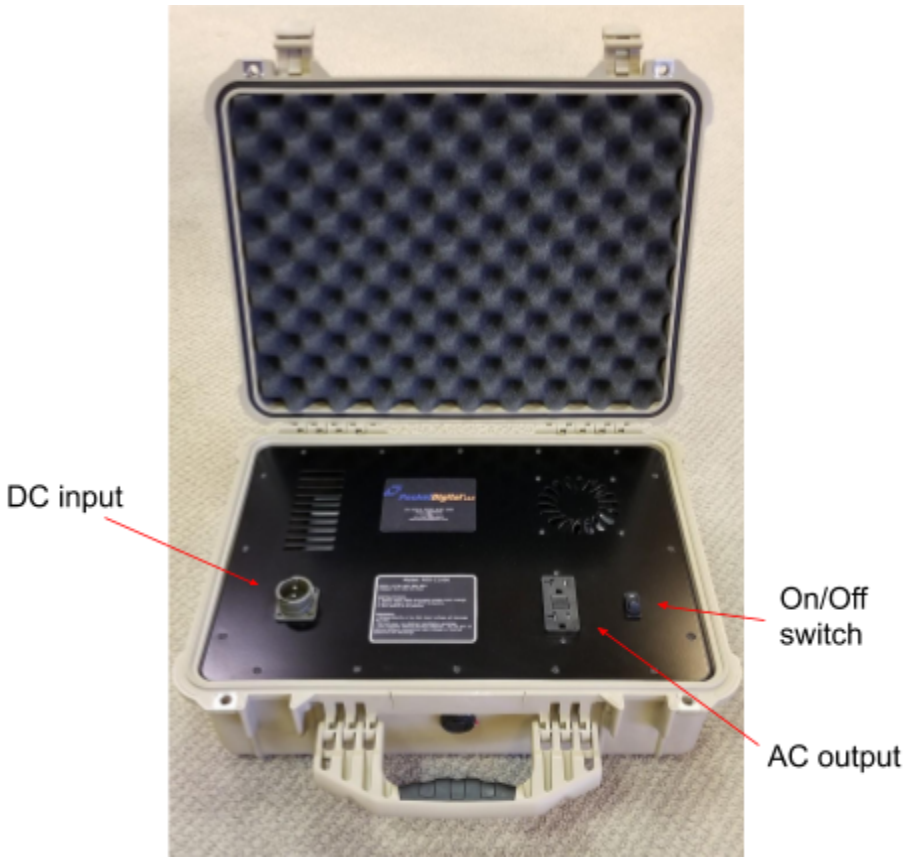

Figure 5: Fully assembled PSG-C1000

Table 2: PSG-C1000 specification

Parameter	Min	Typ	Max	Units
Vin	21	28.8	30	VDC
Input current			40	A
Output Voltage		110		VAC
Output Current		9.1		A
Efficiency		89		%
Storage temperature	-30		70	ºC
Weight		30		Lbs
Dimension (L x W x D)	19.78” x 15.77” x 7.41”			

Objective 2: Evaluate and/or develop a smart battery.

Batteries are a critical part to nearly every aspect of this portable solar generation system. They are the primary medium to store excess solar energy during daytime to be used at a later time when solar power is unavailable.

We have identified and evaluated BB2590 battery to be used as the primary energy storage medium. BB2590 battery is a high performance lithium-ion battery with two independent 14.4V sections that can be connected externally for series 28.8V or parallel 14.4V operations. BB2590 implements SMBus v1.1 communication and utilizes smart battery technology that protects against over-current, over-voltage, over-temperature, under-voltage, and short circuit.

Table 3: BB2590 general specification

Section voltage	14.4V (16.6V max)
Energy capacity	225 Wh
Dimension (L x H x W)	4.4” x 5” x 2.4”
Weight	3.1 lbs
Operating temperature	-4°F - 140°F

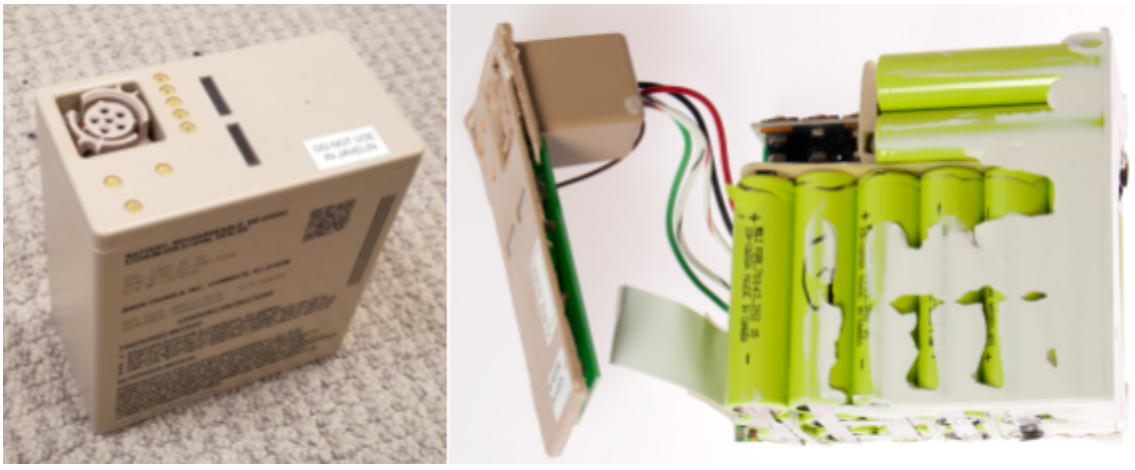

Figure 6: BB2590 battery and its content

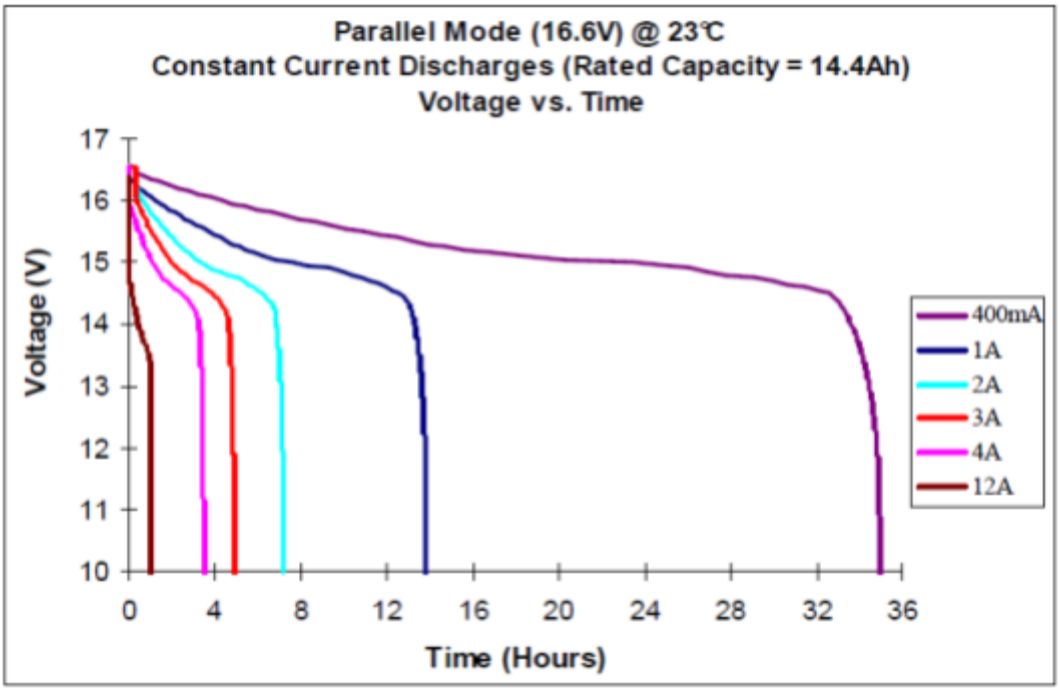

Figure 7: Parallel mode constant current discharge profile

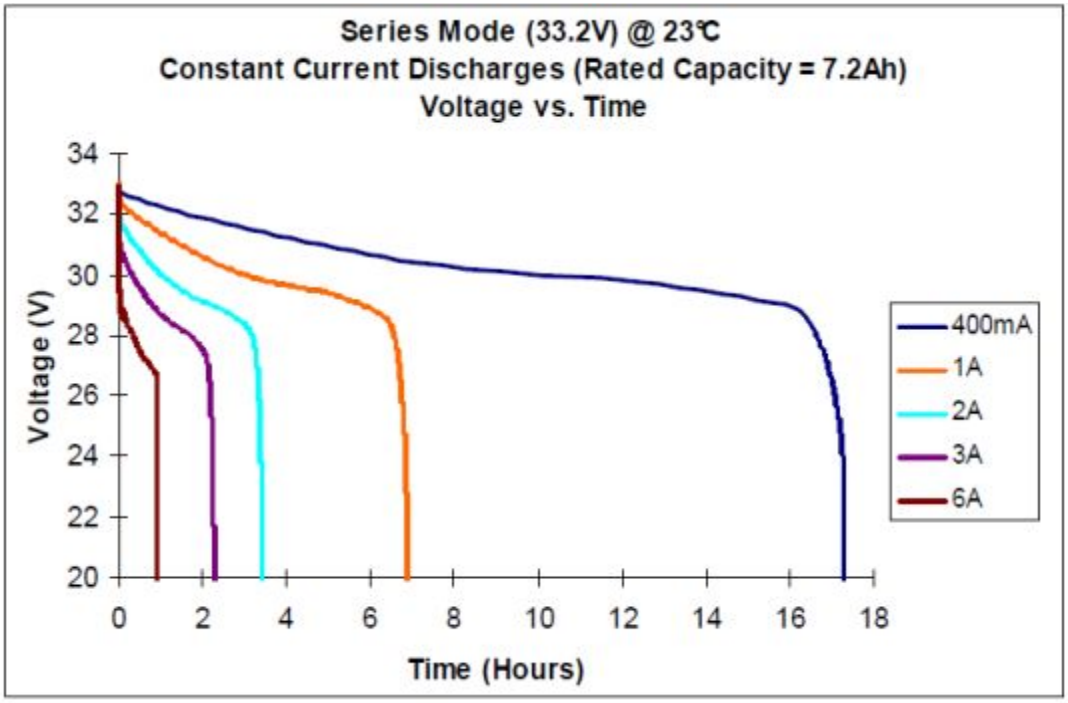

Figure 8: Series mode constant current discharge profile

Objective 3: Create the MPPT charge controller.

From multiple configurations that were evaluated, We have narrowed down the selection into two primary configurations. Final identification and selection was based on the performance and cost tradeoff between the two.

Table 4: Solar panel and MPPT configuration comparison

Panel in series	Panel in parallel
✔ Requires only one MPPT	Requires multiple MPPT
Requires high voltage MPPT	✔ Does not require high voltage MPPT
✔ Very high efficiency under full sun	High efficiency under full sun
Lower efficiency when shaded	✔ Maintain good efficiency when shaded
✔ Less component counts	More component counts
Less system flexibility	✔ More system flexibility
✔ Low overall cost	High overall cost

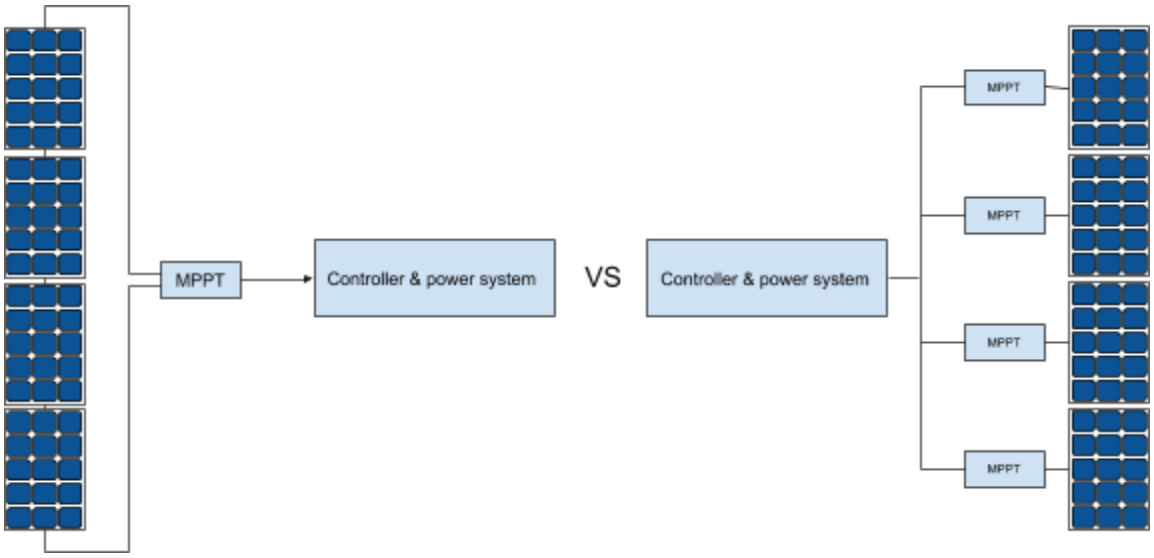

Figure 9: Series and parallel panels and MPPT configuration

We have identified and selected series solar panel configuration with one MPPT as the preferred choice. Prototypes of the MPPT have been designed, fabricated, and successfully tested. The latest MPPT prototype features two LED bar indicators to show the available solar input power (shown in green LED bar) as well as to show how much power being drawn from the system as output power (shown in red LED bar). It is also equipped with four built in USB chargers for charging portable devices. This MPPT will integrate with the remaining modules in the system such as the bidirectional smart battery chargers and output port instrumentation & protection as shown in Figure 2. This integrated electronic system is called PSG1.

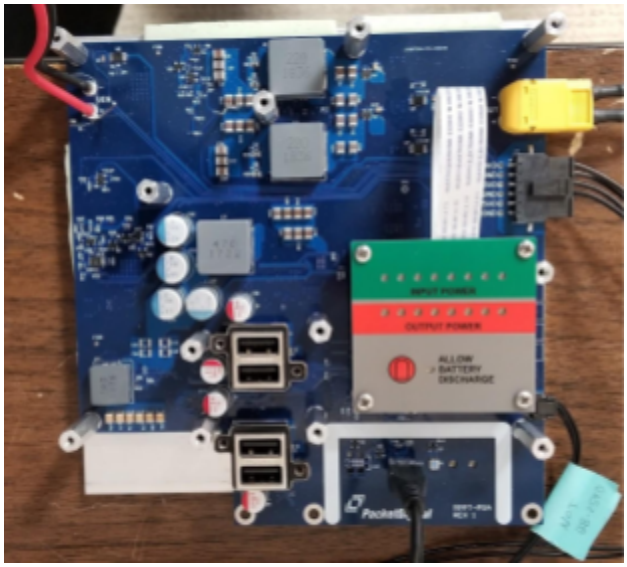

Figure 10: MPPT module

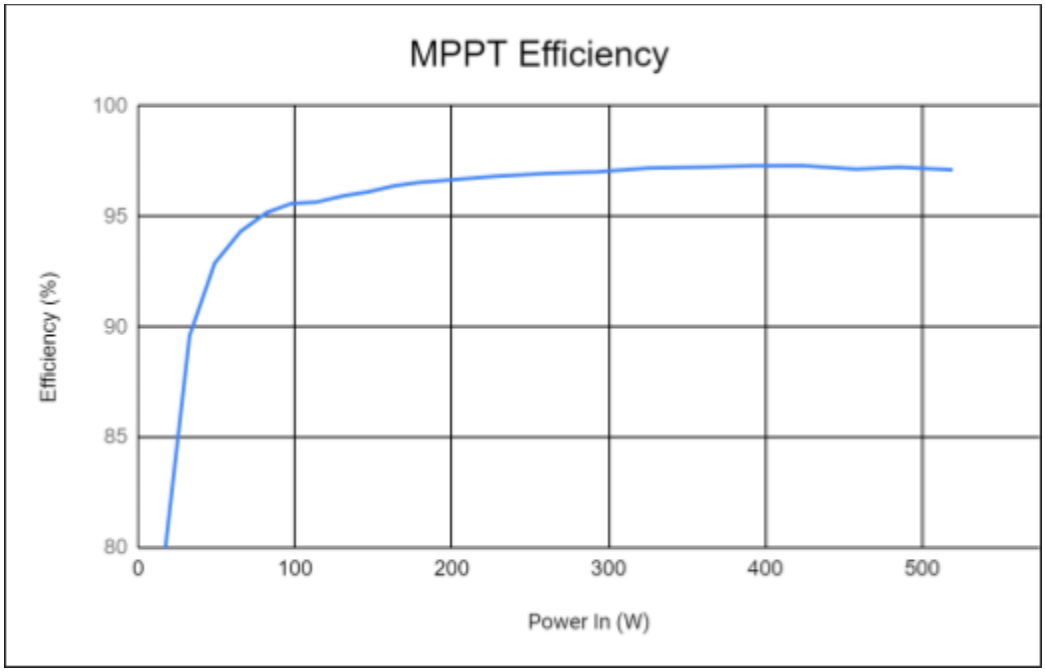

Figure 11: MPPT efficiency profile

Objective 4: Evaluate and develop additional hardware, custom enclosures, and transport cases.

We have evaluated, developed, and prototyped additional hardware modules as part of the overall system as shown in Figure 2. The electronic modules are then integrated and assembled inside a custom enclosure that Packet Digital designed with the help from Red E.

Bi-directional Smart Battery Charger

PSG1 has four identical bi-directional smart battery chargers which not only will charge the BB2590 batteries using solar power, but also will allow the batteries to power the external load through the output port in the event that solar power is not sufficient or not available at all. Each of these smart chargers can deliver up to 150W of power from the BB2590 battery to the output port. Essentially the bi-directional smart charger allows the battery to be charged and discharged depending on the operation conditions.

The smart chargers communicate with the BB2590 batteries through the SMBUS lines, which allow them to obtain the batteries internal information such as the energy

capacity, current state of charge (SOC), temperature, cell voltages, input and output current, and battery warning status. From this communication the chargers can determine the optimum amount of charging current to be delivered to the batteries as well as determine how much energy can be taken from the batteries.

Figure 12: Bi-directional smart battery charger module

Output Port Instrumentation & Protection

The output of PSG1 is delivered through the output port, which can support up to 576W of power at 28.8V. This output port is a step down converter operating under constant voltage current controlled mode with 20A maximum current limit.

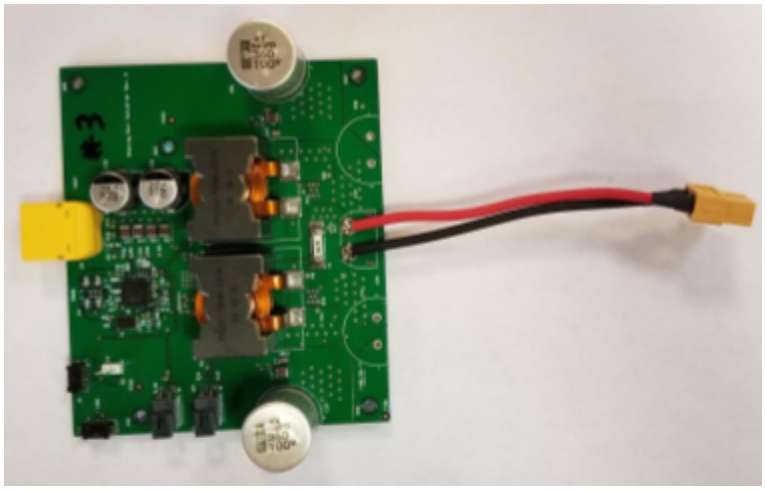

Figure 13: Output port instrumentation & protection module

Custom Enclosure

To contain all the electronic modules in PSG1, a rugged custom enclosure has been designed and fabricated using aluminum for the backplate and ultra high molecular weight (UHMW) polyethylene for the front plate. Both the front plate and backplate were fabricated using computer numerical control (CNC) machining. The aluminum backplate not only will serve as a very good thermal dissipation medium for the heat generated by the electronics, but also will provide a good mechanical support for the whole assembly. The UHMW was selected as the front plate material in this prototype due to its good resistance to wear and the short lead time reasons. For the actual production material we will use polycarbonate instead due to its superior mechanical properties.

Figure 14: Custom enclosure and initial module placement

Objective 5: Final system integration and testing.

Prior to final system integration, several laboratory and field tests were conducted in Fargo, ND. Minor issues were found during the tests and solutions were implemented. Final system integration was completed in mid March 2019 and the fully assembled system was successfully lab and field tested before sending it to Nishati for further test in their facility. Figure x shows the PSG1 efficiency test data from temperature chamber test.

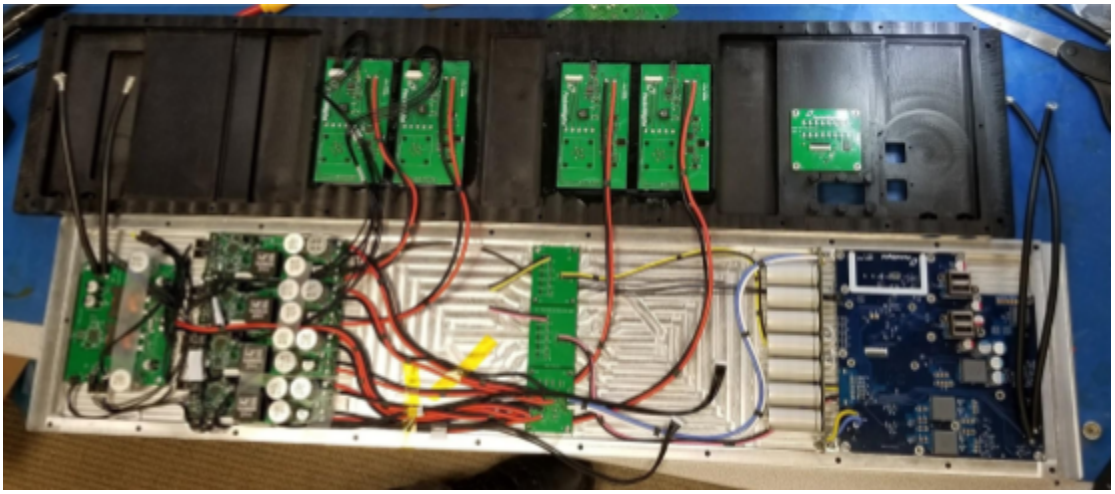

Figure 15: PSG1 integration inside custom enclosure

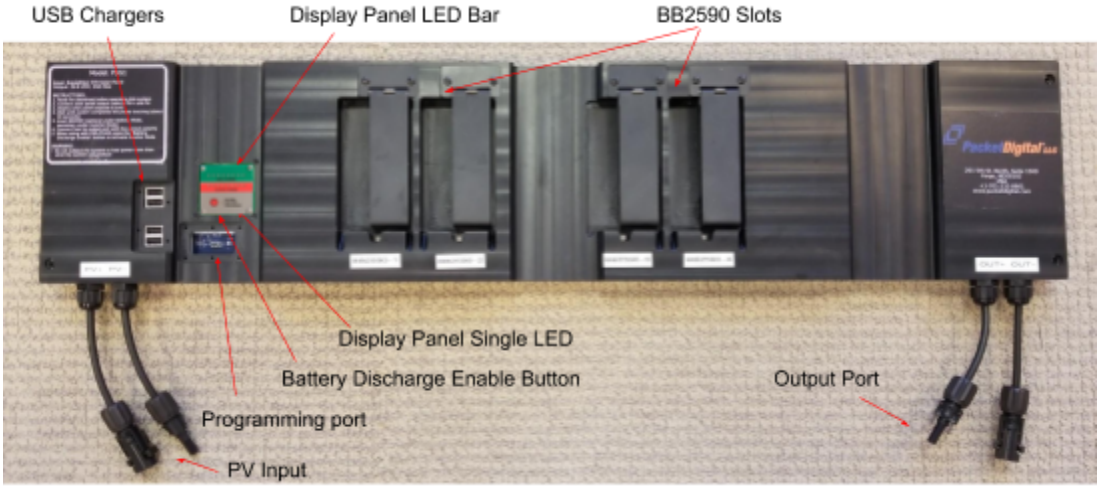

Figure 16: Fully assembled PSG1

Figure 17: Overall PSG1 system efficiency profile

At Nishati's facility in Gilbert, Arizona, more field tests were conducted to reflect the military real use scenarios. Several modifications and enhancements were successfully implemented on PSG1 based on the constructive feedback from Nishati, tailored towards military use.

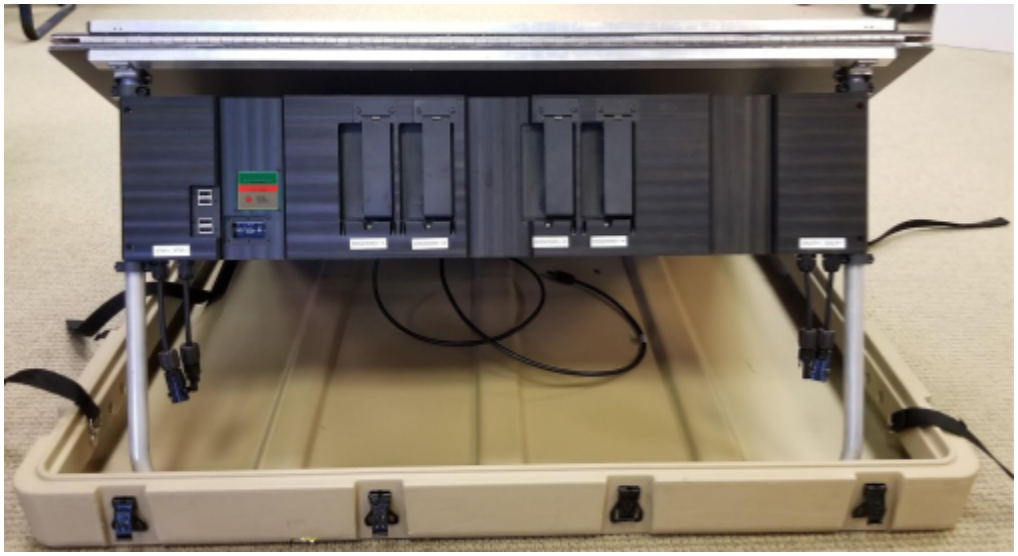

Figure 18: Integration of PSG1 and Expedition 570

Table 5: PSG1 specification

Parameter	Conditions	Min	Typ	Max	Units
Vin from solar panel		48		100	V
Sharing port Vout			28.8		V
BB2590 charger Vout	Charger operation			16.5	V
	Boost operation		48		V
Sharing port Iout				20	A
BB2590 charger Iout	Charger operation			6	A
	Boost operation			3.125	A
USB charger Vout		4.75	5	5.25	V
USB charger Iout				2.33	A
Efficiency	MPPT			>97	%
	PSG1 system			>95	%
Operating temperature		-25		55	°C
Storage temperature		-40		75	°C
Weight	PSG1 without BB2590		12		lbs
	Combined with Expedition 570		112		lbs
Dimension (L x W x D)	PSG1 only	33.5” x 7.5” x 1.5”			
	Combined with Expedition 570	43” x 38.37” x 6.75”			

Objective 6: Develop, document, transition, and implement the manufacturing plan.

Packet Digital has discussed with Chiptronics and a manufacturing plan is in place utilizing Chiptronics’ employees and facilities in Dunseith, ND for electronics manufacturing, including the MPPT, smart battery chargers, and output port electronics.

> *Chiptronics is excited to build the power electronics circuit boards and assemble them into enclosures at their 100,000 ft facility in North Dakota. Chiptronics has access to one of the most tenured electronic assembly workforces in the county and is known across the globe for their high quality standards.*
>
> -- Bill Tuttle, Chiptronics

Packet Digital has also discussed with Nishati about the commercialization and distribution, and Nishati will be our partner for these aspects. Nishati is currently establishing contacts with the military for prototype demonstrations.

In Phase II, the first batch order of four units will be done by Chiptronics for the electronics. This will be a pilot run to test and evaluate manufacturability as well as to anticipate any potential issues early in the manufacturing stage. Mechanical integration for the prototypes will be done by Packet Digital in their Fargo ND office and will be transitioned to Chiptronics for production. Products from this pilot run will be sent for FCC as well as MIL-STD testings and certifications. Upon successful tests and certifications, Nishati will be our primary commercialization partner and distributor.

Budget

Total project cost was expected to be $1,000,000, of which $500,000 was provided by NDIC. Matching funds of $593,076.88 was provided, $75,314.92 by Nishati and $368,561.97 by the Naval Research Lab. Table 6 lists the budget estimate for Phase I, and Table 7 lists the final budget as of April 30, 2019.

Table 6: Budget estimate for Phase I

Project Associated Expense	NDIC Share	Nishati Share	NRL Share	Total
Total Personnel Cost	$480,000	$60,000	$325,000	$865,000
Software and Materials	$20,000	$15,000	$100,000	$135,000
Total	$500,000	$75,000	$425,000	$1,000,000

Table 7: Final budget status for phase I

CUMULATIVE EXPENDITURES					
Project Expense	**NDIC**	**Packet Digital**	**NRL**	**Nishati**	**Total**
Total Personnel Costs	$481,599.38	$143,277.67	$337,102.23	$50,821.84	$1,012,801.12
Software/Materials/Subs	$18,400.62	$5,922.32	$31,459.74	$24,493.08	$80,275.76
Total	$500,000.00	$149,199.99	$368,561.97	$75,314.92	$1,093,076.88

Summary

Project Deliverables:

- Power electronics and hardware for a portable 1kW solar power system, including 1kW inverter, smart batteries, and MPPT
    - Design and construction of PSG1 with integrated MPPT.
    - Construction of PSG-C1000, incorporating 1kW inverter.
    - Identification and use of military smart battery BB2590 in the system.
- Innovative MPPT algorithm for extracting maximum charging capacity from the solar cells
    - Greater than 97% efficient MPPT algorithm with rapid convergence.
- Custom enclosures for individual electronic components and integrated system
    - Aluminum backplate and UHMW front plate for PSG1 electronics, custom designed to perfectly fit into the Expedition 570 solar panel case.
- Documented results of system testing
    - Successful laboratory and field tests of the portable solar system.
    - Datasheet creation for PSG1 and PSG-C1000
- Manufacturing ready for a commercially viable, portable 1kW solar power system
    - Manufacturing ready prototypes for PSG1 and PSG-C1000 have been built.
    - Expedition 570 solar panel is available through Nishati and is manufacturing ready.
- Commercialization partners and distribution
    - Nishati will be our commercial partner and distributor.